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(54) Title: METHOD AND SYSTEM FOR THE EXAMINATION OF SPECIMEN USING A CHARGED PARTICLE BEAM
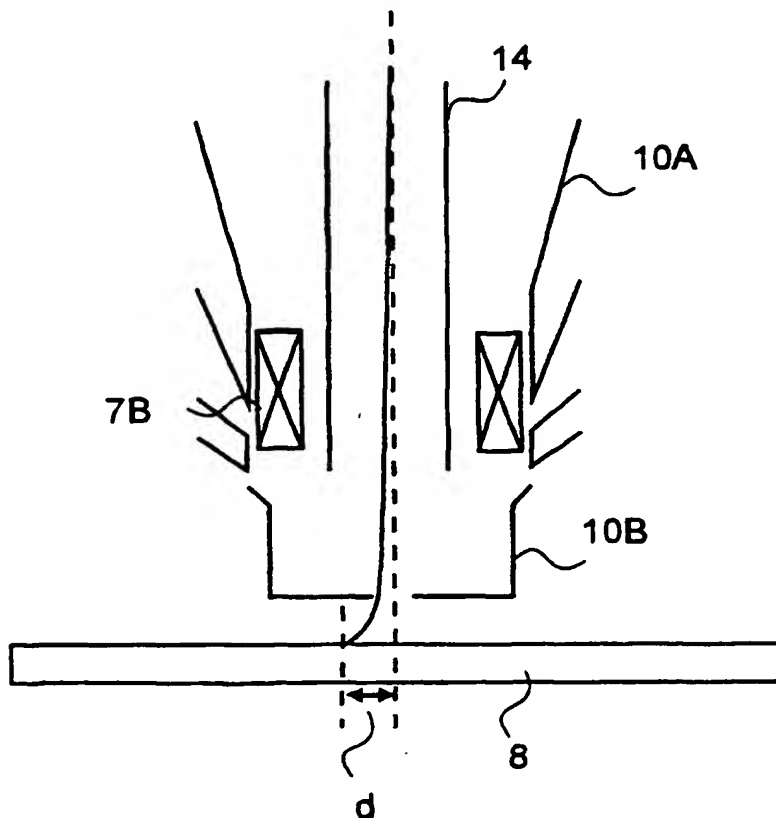
(57) Abstract: The present invention provides a method for the examination of specimen with a beam of charged particles. The method provides one or more images of the specimen made with different view angles, so that, compared to a single image of the specimen, a lot of additional information about the specimen can be accessed. The different view angles (angles of incidence) are achieved by tilting the beam between the two images and moving the specimen to a new position so that the displacement of the beam caused by the tilting of the beam is compensated. Accordingly, while displaying/recording the second image the beam scans over the same area as it has scanned while displaying/recording the first image. A deflection and focussing system for the compensation of chromatic aberration and examples of accurate measurements of structures on the surface of a semiconductor are also described.

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METHOD AND SYSTEM FOR THE EXAMINATION OF SPECIMEN USING A CHARGED PARTICLE BAM

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FIELD OF THE INVENTION

10   The invention relates to a method and a system for the examination of specimen. Especially, the invention relates to a method and a system for the examination of specimen with a beam of charged particles.

15   BACKGROUND OF THE INVENTION

The resolution of the conventional optical microscopy is limited by the wavelength of the visible light. Furthermore, at the highest resolution the
20   conventional optical microscopy has a very shallow depth of field. These two limitations have led to the increased popularity of charged particle devices for the examination of specimen. Compared to optical light accelerated charged particles, for example electrons, do exhibit a shorter wavelength, which leads to an increased resolution power. Accordingly, charged particle beams, especially
25   electron beams, are used in a variety of ways in biology, medicine, the materials sciences, and lithography. Examples include the diagnosis of human, animal, and plant diseases, visualization of sub cellular components and structures such as DNA, determination of the structure of composite materials, thin films, and ceramics, or the inspection of masks and wafers used in
30   semiconductor technology.

Furthermore, charged particle devices are well suited for the examination of the microstructure of solid surfaces. Especially, the scanning electron microscope is a versatile instrument for examining the microstructure of a
35   surface, because it combines high spatial resolution with depth of field in the

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same image, and requires only minimal sample preparation. Modern instruments distinguish features as small as 1 nm, while retaining crisp focus throughout tens of microns in the vertical direction. Hence, it is well suited for routine inspections of the intricate surface details of highly integrated circuits.

5   Charged particle devices may, for example, be used in order to monitor the quality of the wafer processing in the semiconductor industry. Thereby, the device is actually located within the production environment, so that problems of the wafer processing are recognized as soon as possible.

10   However, conventional charged particle devices are not capable of providing accurate critical dimension, accurate height or accurate edge width measurements without the need of massive manual interference. In order to measure, for example, the height difference between two image points, usually two images are recorded with a defined specimen tilt between the exposures.

15   However, mechanically tilting the specimen leads to a number of disadvantages. Due to mechanical imperfections a lateral movement of the specimen is inevitable which often results in misregistrations between the elements of a stereo image pair. Accordingly, additional alignments are necessary which slow down the process considerably. Furthermore, tilting

20   large specimen, for example a 12 inch semiconductor wafer, requires a very robust and costly mechanical configuration in order to guarantee an adequate resistance of such a stage against vibrations.

In order to overcome the problems connected with a mechanical tilt of the

25   specimen, it has been proposed to tilt the electron beam electrically in the electron-optical column to procure the same result, see e.g. B.C. Brenton et al. "A DYNAMIC REAL TIME 3-D MEASUREMENT TECHNIQUE FOR IC INSPECTION", Microelectronic Engineering 5 (1986) 541 – 545, North Holland or J.T.L. Thong et al. "In Situ Topography Measurement in the SEM",

30   SCANNING Vol. 14, 65 –72 (1992), FAMS, Inc.. However, the height resolution of the proposed systems lies in the range of 75 to 100 nm, which is not sufficient for the requirements of the semiconductor industry.

Due to these problems, critical dimension measurements and side wall

35   profiling are often done with an atomic force microscope. However, using an

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atomic force microscope requires an additional experimental setup which increases the costs significantly and is also very slow. Accordingly, there is a need for a faster and more automated method of examing a specimen which allows accurate critical dimension, accurate height or accurate edge width
5   measurements.

SUMMARY OF THE INVENTION

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The present invention provides a method for the examination of specimen with a beam of charged particles. The method provides one or more images of the specimen made with different view angles, so that, compared to a single top view image of the specimen, a lot of additional information about the specimen
15   can be accessed. The different view angles (angles of incidence) are achieved by tilting the beam between the two images and moving the specimen to a new position so that the displacement of the beam caused by the tilting of the beam is compensated. Accordingly, while displaying/recording the second image the beam scans basically over the same area as it has scanned while
20   displaying/recording the first image. The present invention also provides an apparatus for the examination of specimen that is capable of performing this improved method.

By providing an oblique angle of incidence on the one hand and a
25   corresponding movement of specimen on the other hand, stereo images of a specimen can be produced in a fast and reliable manner without the need for any additional alignments and without the need for excessive image processing. Accordingly, the additional information, which is contained in stereo images and which is extremely valuable in many cases, can be accessed without
30   causing any additional costs.

According to a further aspect of the present invention, a method for directing a beam of charged particles onto the surface of a specimen under a predetermined angle of incidence is provided. The predetermined angle of
35   incidence is achieved by the combined action of deflecting the beam away from

the optical axis of an objective and focusing the beam onto the specimen. The deflection is done in at least two steps which are adjusted to each other so that the chromatic aberrations on the surface of the specimen are minimized. The present invention also provides a column for directing a beam of charged particles onto the surface of a specimen that is capable of performing this improved method.

It has been found by the present inventors that the chromatic aberrations caused by the first step of the deflection can be compensated to a large extent by the second step of the deflection if the two deflections are properly adjusted. The combined action of the two step deflection and focussing of the beam then leads to a resolution in the range of a few nanometers, which is comparable with the resolution that can be achieved without providing an oblique angle of incidence. The invention has thus the advantage that large angles of incidence on a specimen can be provided without a reduction in resolution arising from large chromatic aberrations.

According to a still further aspect of the present invention, methods are provided that allow an accurate measurement of important distances on the surface of a specimen, especially on the surface on a semiconductor wafer. These methods use a tilted beam of charged particles to get the information in a very fast and reliable manner.

BRIEF DESCRIPTION OF THE DRAWINGS

Some of the above indicated and other more detailed aspects of the invention will be described in the following description and partially illustrated with reference to the figures. Therein:

Fig. 1 is a schematic diagram of a charged particle apparatus according to a first embodiment of the present invention.

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Fig. 2 is a schematic diagram of a charged particle apparatus according to a second embodiment of the present invention.

Fig. 3 is a schematic diagram of a charged particle apparatus according to a
5   third embodiment of the present invention..

Fig. 4 is an enlarged view showing the objective lens of the embodiment of Fig. 3.

10   Fig. 5 is an enlarged view of Fig. 4.

Fig. 6A and Fig. 6B show a pillar which extends from a flat surface and whose height is to be determined.

15   Fig. 7A and Fig. 7B show a contact hole which is extending downward from a flat surface and whose width at its bottom is to be determined.

Fig. 8A and Fig. 8B show a line which is extending upward from a flat surface and whose width at its bottom is to be determined.
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Fig. 9A and Fig. 9B show a top view and a tilt view of a trench present on the surface of a wafer.

Fig. 10A and Fig. 10B show a top view and a tilt view of a line present on the
25   surface of a wafer.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

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Preliminary, it should be appreciated by those skilled in the art that the present invention can be used with any charged particle device. However, for convenience, the invention will be described with respect to its implementation in a scanning electron microscope (SEM). A preferred embodiment according
35   to the invention is shown schematically in Fig. 1. The basic components of the

device are an electron source 2, a lens system (condenser lens 5 and objective lens 10), scanning coils 12A and 12B, beam shift coils 7 and a detector 16. In operation an electron beam 4 is emitted from the electron source 2. The electron source may, for example, be a tungsten-hairpin gun, a lanthanum-

5 hexaboride gun, or a field-emission gun. The electrons are accelerated by an accelerating voltage supplied to the electron source 2. Since the beam diameter produced directly by the electron source usually is too large to generate a sharp image at high magnification, the electron beam 4 is guided through the condenser lens 5, which demagnifies the beam and leads the electron beam 4

10 towards a specimen 8.

The electron beam 4 then enters the field of the deflector 7A which deflects the electron beam 4 away from its path along the optical axis of the objective lens 10. The deflector 7A is followed by the scanning coils 12, which

15 are used to move the electron beam 4 in a television-like raster over the surface of the specimen 8. After the scanning coils 12 the electron beam 4 enters the objective lens 10 that focuses the electron beam 4 onto the specimen 8. The objective lens 10 not only focuses the electron beam 4 but also rotates the electron beam 4. However, this effect is not shown, because it is difficult to

20 depict in a two-dimensional drawing and because the skilled person is well aware of this additional effect.

Due to the combined action of the deflector 7A and the objective lens 10, the electron beam 4 hits the specimen under a predetermined angle of

25 incidence, preferably in the range between 1° and 20° degrees. When the electrons strike the surface of the specimen 8, a variety of secondary products, such as electrons of different energy, X rays, light, and heat, as well as electrons scattered backward are produced. Many of these secondary products and/or the backscattered charged particles are used to produce the image of the

30 specimen and to collect additional data from the specimen. A secondary product of major importance to examination or the image formation of specimens are secondary electrons that escape from the specimen 8 at a variety of angles with relatively low energy (3 to 50 eV). The secondary and the back scattered electrons reach the detector 16 and are measured. By scanning the

electron beam over the specimen and displaying/recording the output of the detector 16 an image of the surface of the specimen 8 is formed.

5   The specimen 8 is supported on a stage 11 (specimen support) which is moveable horizontally in all directions, in order to allow the electron beam 4 to reach the target areas on the specimen which are to be examined. When the specimen 8 is viewed under an oblique angle of incidence, the electron beam does not hit the specimen along the optical axis but it is displaced from the optical axis. Therefore, the stage 11 performs a corresponding movement with

10   the specimen 8 so that the electron beam hits the same area on the specimen that would have been hit if the electron beam had not been deflected by the beam shift coils 7A. When the deflection of the electron beam 4 and, accordingly, the angle of incidence is changed, for example to produce a pair of stereo images, the stage 11 again moves the specimen 8 to a new position so

15   that the displacement of the beam caused by the tilting of the beam is compensated. Accordingly, any misregistration between the two images can basically be avoided.

By providing an oblique angle of incidence on the one hand and a

20   corresponding movement of specimen on the other hand, stereo images of a specimen can be produced in a fast and reliable manner without the need for any additional alignments. Accordingly, the additional information, which is contained in stereo images and which is extremely helpful in many cases, can be accessed without causing any additional costs. Normally, both images of a

25   stereo pair are produced using an oblique angle of incidence. However, depending on the application, one of the stereo images may also be produced by using a top view of the specimen ($\theta = 0°$).

The embodiment shown in Fig. 1 uses a pre-lens deflector 7A in order to

30   deflect the electron beam 4. The deflection of the electron beam 4 leads to an off-axis path of the beam through the objective lens 10 which gives rise to chromatic aberrations.

In order to decrease the chromatic aberrations, Fig. 2 shows a schematic

35   diagram of an apparatus according to a further embodiment of the present

invention. This embodiment is similar to that of Fig. 1, except for the following. The pre-lens deflector 7A has been replaced by an in-lens deflector 7B that is located within the objective lens 10. When the deflector 7B is placed inside the field of the objective lens 10, the chromatic aberrations are reduced

5 considerably. The reduction can amount to 50% or more, if the deflector 7B is placed deep inside the field of the objective lens 10 or even partly below the objective lens 10.

In order to further improve the performance of system, the embodiment

10 shown in Fig. 2 contains a reference target 40 integrated into the stage 11. The reference target 40 is used to determine the precise angle of incidence of the electron beam 4 hitting the reference target 40. For example, the reference target may contain a repeating structure of lines or trenches which exhibit vertical walls. By moving the stage 11 so that the reference target 40 comes

15 within the scanning range of the electron beam 4, images of the reference target 40 can be used to measure the angle of incidence and to find a parameter setting (for example for the deflector 7B, the objective lens 10, the beam energy, etc.) so that electron beam 4 hits the reference target 40 with predetermined angle of incidence. Once this parameter setting has been found,

20 it can be used for precise measurements on the actual specimen 8 later on.

In the embodiment shown in Fig. 2 the reference target 40 is integrated into the stage 11. However, the reference target 40 might as well be provided on a separate support, which for example can be rotated in order to bring the

25 reference target 40 within the scanning range of the electron beam 4. Furthermore, a heating system (not shown) can be provided for the reference target 40 so that by heating the reference target 40 contaminants present on the surface of the target are evaporated. By heating the reference target from time to time a clean reference target can be guaranteed over long period of time.

30 Accordingly, the down time of the complete system can be reduced.

In order to further decrease the chromatic aberrations, Fig. 3 shows a schematic diagram of an apparatus according to a further embodiment of the present invention. This embodiment is similar to that of Fig. 1 and Fig. 2,

35 except for the following. Instead of using either a pre-lens deflector 7A or an

in-lens deflector 7B, the embodiment shown in Fig. 3 uses the pre-lens deflector 7A and the in-lens deflector 7B in combination. It has been found by the present inventors that the chromatic aberrations caused by a first deflector, in this example the pre-lens deflector 7A, can be compensated to a large extent
5   by a second deflector, in this example the in-lens deflector 7B, if the deflections caused by these coils are properly adjusted. In the present example a pre-lens deflector 7A and an in-lens deflector 7B are used. However, it is also possible to use two pre-lens deflectors or two in-lens deflectors to achieve the same results.
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The precise adjustment of the two deflections depends on a number of parameters, for example the chosen angle of incidence, the beam energy, the objective lens current, etc.. However, the practice of the invention does not depend on a precise knowledge of these parameters and their effects on the
15   chromatic aberrations caused by the beam deflection. The direction of the deflection and the angle of deflection of the pre-lens and the in-lens deflector at which for a preselected angle of incidence minimum aberration is obtained may be extracted experimentally from the resulting images, either from the images of the specimen 8 itself or from images of the reference target 40. The
20   combined action of the pre-lens deflector and the in-lens deflector then lead to a resolution in the range of a few nanometers, which is comparable with the resolution that can be achieved without providing an oblique angle of incidence. The invention has thus the advantage that large angles of incidence on a specimen can be provided without a reduction in resolution arising from
25   large chromatic aberrations.

In order to further improve the performance of system, the embodiment shown in Fig. 3 contains an objective lens 10 which is a combination of a magnetic lens 10A and an electrostatic lens 10B. Accordingly, the objective
30   lens 10 is a compound magnetic-electrostatic lens. Preferably, the electrostatic part of the compound magnetic-electrostatic lens 10 is an electrostatic retarding lens 10B. Using such a compound magnetic-electrostatic lens 10 yields superior resolution at low acceleration energies, such as a few hundred electron volts in case of a SEM. Such low acceleration energies are desirable,

especially in modern semiconductor industry, to avoid charging and/or damaging of radiation sensitive specimens.

Figures 4 and 5 show enlarged views on the compound magnetic-
5   electrostatic lens 10 and the specimen 8 as shown in Fig. 3. To achieve a small focal length, the magnetic flux generated by a current through an excitation coil is conducted through pole pieces and is concentrated into a small region along the optical axis of the magnetic lens. The magnetic field is rotational symmetric around the optical axis and reaches its maximum value in the pole
10   gap between the upper and the lower pole piece. Furthermore, the beam shift coils 7B are placed inside the magnetic field of the objective lens 10A, so that there is considerable overlap between their respective fields.

In addition to the magnetic lens 10A the embodiment shown in Figs. 3 to
15   5 contains an electrostatic retarding lens which is situated close to magnetic lens 10A. The electrostatic retarding lens 10B has two electrodes held at different potentials. In the illustrated embodiment one of the two electrodes is formed by a cylindrical beam tube 14 which is arranged within the magnetic lens 10A along the optical axis. The second electrode of the electrostatic
20   retarding lens 10B is a metallic cup provided below the magnetic lens 10A. In operation of the system the first electrode is usually held at high positive potential, for example 8 kV, where as the second electrode is held at lower positive potential, for example 3 kV, so that the electrons are decelerated in the corresponding electrostatic field from a first energy to lower second energy.
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In the example shown in Figs 4 and 5 the specimen 8 is held at ground potential. Accordingly, there is a further electrostatic retarding field between the metallic cup and the specimen 8. Due to the electrostatic retarding field between the metallic cup and the specimen 8, an initial deflection of the
30   electron beam 4 caused by the beam shift coils 7A and 7B is enhanced leading to an increased angle of incidence. Accordingly, in order to achieve a predetermined angle of incidence only small deflections caused by the beam shift coils 7A and 7B are necessary.

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The surface of the specimen need not be grounded. The electric potential on the surface of the specimen may also be adjusted by applying a voltage to the specimen. A voltage can be applied to a wafer, for example, in order to obtain voltage contrast imaging which is used to detect shorts in a circuit. As

5 long as the potential of the metallic cup is higher than the potential on the surface of the specimen, an electrostatic retarding field is produced.

As can be seen from Fig. 5, when the specimen 8 is viewed under an oblique angle of incidence θ, as measured with regard to an axis normal to the

10 surface of the specimen, the electron beam does not hit the specimen along the optical axis of the objective lens 10. The electron beam 4 is displaced from the optical axis by a distance d. Therefore, the stage 11 performs a corresponding movement with the specimen 8 so that the electron beam hits the same area on the specimen that would have been hit, if the electron beam had not been

15 deflected by the beam shift coils 7A. When the deflection of the electron beam 4 and, accordingly, the angle of incidence θ is changed, for example to -θ, the stage 11 again moves the specimen 8 to a new position so that any misregistration between the two images can basically be avoided.

20 Fig. 6A and Fig. 6B together with following description will explain how according to the present invention an accurate height measurement is performed. Fig. 6A and Fig. 6B show a pillar which extends from a flat surface. Fig. 6A is an image of the pillar taken with a beam tilt of $\theta_L = -3°$ whereas Fig. 6B is an image of the pillar taken with a beam tilt of $\theta_R = +3°$

25 with respect to an axis normal to the flat surface.

To determine the height difference Δh between the top of the pillar and the bottom surface a distinctive feature has to be located for each level. On top of the pillar the right end of a flake was used as the first distinctive feature. On

30 the bottom surface the end of a particle was used as the second distinctive feature. In both images the distance in X-direction between the two features is measured, P1 for Fig. 6A and P2 for Fig. 6B. The difference P between the distance P1 and the distance P2 (P = P1 − P2, P is called the parallax) is then used in order to calculate the height difference Δh between the top of the pillar

35 and the bottom surface. The height difference Δh is given by the formula:

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$$\Delta h = P*((\sin\theta_R * \sin\theta_L)/(\sin\theta_R - \sin\theta_L))$$

For small angle approximation (θ_R, $\theta_L \leq 5°$) the height difference can also
5 be given by:

$$\Delta h = P/(2*\sin((\theta_R - \theta_L)/2)).$$

In the example shown in Figures 6A and 6B the distance P1 corresponds
10 to 0.546 μm whereas the distance P2 corresponds to 0.433 μm. Accordingly,
the height difference Δh between the top of the pillar and the bottom surface in
this example is 1.079 μm.

Due to the present invention it does not take any extra effort to gain
15 additional height information from the specimen. However, this additional
information is often extremely valuable, particularly on specimens whose
topography is complex. In this example the height of a pillar was determined.
It is clear, however, that the same procedure can also be used to determine the
depth of a trench or a hole. In case of a semiconductor wafer the accurate
20 depth of a trench, for example the depth of an isolation trench, or the accurate
depth of a contact hole is extremely useful information in order to control the
quality of the production process.

Once the depth of a trench or a hole or the height of a line is known, this
25 information can be used in order to determine further interesting features. For
example, by knowing the depth of a contact hole, a further embodiment of the
present invention can be used, in order to determine the true width of the
contact hole at its bottom. Fig. 7A and Fig. 7B show a contact hole extending
downward from a flat surface. Fig. 7A is an image of the contact hole taken
30 with a beam tilt of $\theta_L = -3°$ whereas Fig. 7B is an image of the contact hole
taken with a beam tilt of $\theta_R = +3°$ with respect to an axis normal to the flat
surface.

In Fig. 7A (left view) the left top edge T_1, the right top edge T_2 and the
35 right bottom edge B_L of the contact hole can be seen. In Fig. 7B (right view)

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again the left top edge T_1 and the right top edge T_2 can be seen. Furthermore, the left bottom edge B_R of the contact hole is visible. By measuring the visible distances T_1B_L and T_1T_2 as measured in Fig. 7A , the left view, and the distance T_2B_R as measured in Fig. 7B, the right view, the true width W_b of the contact

5   hole at its bottom can be calculated:

$$W_b = T_1B_L/\cos\theta_L + T_2B_R/\cos\theta_R + h(\tan\theta_L + \tan\theta_R) - W_t$$

where h is the depth of the contact hole and W_t is the width of the contact

10   hole at the top. In the present example W_t is given by $T_1T_2/\cos\theta_L$. In the example shown in Figures 7A and 7B the distance $T_1B_L/\cos\theta_L$ corresponds to 0.29 μm, the distance $T_2B_R/\cos\theta_R$ corresponds to 0.334 μm and the distance $T_1T_2/\cos\theta_L$ corresponds to 0.4005 μm. Furthermore, the depth h of the contact hole was determined to be 1.0 μm. Accordingly, the true width W_b of the

15   contact hole at its bottom in this example is 0.324 μm.

The method has the advantage that true width W of the contact hole at its bottom can be determined even for contact holes having high aspect ratio (deep and narrow). This is in contrast to other methods, like the atomic force

20   microscopy, which exhibit extreme difficulties in these cases.

In addition to the determination of the true width W of the contact hole at its bottom, a further embodiment of the present invention can be used, in order to determine the width of a sidewall which is visible in the figures 7A or 7B.

25   For example, from Fig. 7B the width of the left sidewall of the contact hole can be determined. The width of the sidewall in this context means the lateral distance in horizontal wafer plane direction between the top of the sidewall and the bottom of the sidewall. By measuring the visible distance T_2B_R as measured in Fig. 7B the true width W_L of the left sidewall of the contact hole

30   can be calculated:

$$W_L = W_t - T_2B_R/\cos\theta_R - h\tan\theta_R$$

where T_2B_R is the visible distance as measured between the bottom edge

35   of the sidewall and the top edge on the opposite side of the trench or hole, h is

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the depth of the trench or hole, W_t is the width of the trench or hole at the top of the trench or the hole, and θ_R is the viewing angle of the image of Fig. 7B.

Similarly, by measuring the visible distance T_1B_L as measured in Fig. 7A the true width W_R of the left sidewall of the contact hole can be calculated:

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$$W_R = W_t - T_1B_L/\cos\theta_L - h\tan\theta_L$$

where T_1B_L is the visible distance as measured between the bottom edge of the sidewall and the top edge on the opposite side of the trench or hole, h is
10   the depth of the trench or hole, W_t is the width of the trench or hole at the top of the trench or the hole, and θ_L is the viewing angle of the image of Fig. 7A.

According to a further embodiment of the present invention, by knowing the height of a line a pair of stereo images of that line can be used in order to
15   determine the true width of the line at its bottom. Fig. 8A, the left view, and Fig. 8B, the right view, show a line extending upward from a flat surface. Fig. 8A is an image of the line taken with a beam tilt of $\theta_L = -3°$ whereas Fig. 8B is an image of the line taken with a beam tilt of $\theta_R = +3°$ with respect to an axis normal to the flat surface.

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In Fig. 8A the left bottom edge X_1, the left top edge X_2 and the right top edge X_3 of the line can be seen. In Fig. 8B again the left top edge Y_3 and the right top edge Y_2 can be seen. Furthermore, the right bottom edge Y_1 of the line is visible. By measuring the visible distances X_1X_2 and X_2X_3 as measured
25   in Fig. 8A and the visible distances Y_1Y_2 and Y_2Y_3 as measured in Fig. 8B the true width W_b of the line at its bottom can be calculated:

$$W_b = (X_1X_2+X_2X_3)/\cos\theta_L + (Y_1Y_2+Y_2Y_3)/\cos\theta_R - h(\tan\theta_L + \tan\theta_R) - W_t$$

30   or

$$(X_1X_2+X_2X_3 = X_1X_3 \, , \, Y_1Y_2+Y_2Y_3 = Y_1Y_3)$$

or
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$$W_b = X_1X_3/\cos\theta_L + Y_1Y_3/\cos\theta_R - h(\tan\theta_L + \tan\theta_R) - W_t$$

where h is the height of the line and W_t is the width of the feature at the top of the feature. For example, W_t is given by $Y_2Y_3/\cos\theta_R$.. In the example shown in Figures 8A and 8B the distance $(X_1X_2 + X_2X_3)/\cos\theta_L$ corresponds to 0.274 μm, the distance $(Y_1Y_2 + Y_2Y_3)/\cos\theta_R$ corresponds to 0.312 μm and the distance $Y_2Y_3/\cos\theta_R$ corresponds to 0.232 μm. Furthermore, the depth h of the line was determined to be 0.8 μm. Accordingly, the true width W_b of the line at its bottom in this example is 0.27 μm.

Instead of the above presented formula, further equivalent formula can also be used, for example:

$$W_b = X_1X_2/\cos\theta_L + (Y_1Y_2+Y_2Y_3)/\cos\theta_R - h(\tan\theta_L + \tan\theta_R)$$

or

$$W_b = (X_1X_2+X_2X_3)/\cos\theta_L + Y_1Y_2/\cos\theta_R - h(\tan\theta_L + \tan\theta_R)$$

or

$$W_b = X_1X_2/\cos\theta_L + Y_1Y_2/\cos\theta_R - h(\tan\theta_L + \tan\theta_R) + W_t.$$

Again, this method has the advantage that true width W of the line at its bottom can be determined even for lines having high aspect ratio (high and narrow). This is in contrast to other methods, like the atomic force microscopy, which exhibit extreme difficulties in these cases.

In addition to the determination of the true width W of the line at its bottom, a further embodiment of the present invention can be used, in order to determine the the width of a sidewall which is visible in the figures 8A or 8B. For example, from Fig. 8B the width of the right sidewall of the line can be determined. The width of the sidewall in this context means the lateral distance in horizontal direction between the top of the sidewall and the bottom

of the sidewall. By measuring the visible distance Y_1Y_2 as measured in Fig. 8B the true width W_R of the right sidewall of the line can be calculated:

$$W_R = Y_1Y_2/\cos\theta_R - h\tan\theta_R$$

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where Y_1Y_2 is the visible distance as measured between the bottom edge and the top edge of the sidewall of the feature, h is the height of the feature, and θ_R is the viewing angle of the image of Fig 8B.

Similarly, by measuring the visible distance X_1X_2 as measured in Fig. 8A

10   the true width W_L of the left sidewall of the line can be calculated:

$$W_L = X_1X_2/\cos\theta_L - h\tan\theta_L$$

where X_1X_2 is the visible distance as measured between the bottom edge

15   and the top edge of the sidewall of the feature, h is the height of the feature, and θ_L is the viewing angle of the image of Fig 8A.

Fig. 9A and Fig. 9B show a top view and a tilt view of a trench present on the surface of a wafer. As can be seen from Fig. 9B, the tilt view makes it

20   possible to see and to define the true character of the sidewall of the trench. In the tilt view the sidewall can be seen much better and with significantly more details which are undetectable in Fig. 9A, the top view. Accordingly, a sidewall profile of the left sidewall of the trench can be compiled from Fig. 9B. Furthermore, by looking at same edge portions in both images, it is easy to see

25   that the edge in the tilt view captures about twice as many pixels as in the top view. Obviously, this leads to a measurement of the edge width having a significantly better accuracy.

Fig. 10A and Fig. 10B show a top view and a tilt view of a line present

30   on the surface of a wafer. Again, the tilt view (Fig. 10B) makes it possible to see and to define the true character of the sidewall of the line. In the tilt view the side wall can be defined as T-top and its profile can be determined. In the top (Fig. 10A) the T-top is undetectable.

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While the invention has been described with reference to various exemplary embodiments thereof, those of ordinary skill in the art would appreciate that various implementations and variations are possible without departing from the scope and spirit of the invention, as defined by the appended

5   claims. For example, it should be readily apparent that angles and the height and width dimension presented with regard to Figures 6 to 8 are only examples and that other angles, height and width dimension can be used. Similarly, the configuration of the objective lens is provided as example only, and other configurations of the objective lens may be used.

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CLAIMS

1.   A method for the examination of specimen with a beam of charged particles, said method comprising the steps of:

    a)   scanning the beam over the specimen, to produce a first image, whereby the beam hits the surface of the specimen at a first angle of incidence;

    b)   tilting the beam and moving the specimen to a position corresponding to the tilting of the beam so that the beam hits the surface of the specimen at a second angle of incidence and that the displacement of the beam caused by the tilting of the beam is basically compensated; and

    c)   scanning the beam over the specimen, to produce a second image, whereby the beam hits the surface of the specimen under the second angle of incidence.

2.   The method according to claim 1 wherein the tilting of the beam is achieved by the combined action of deflecting the beam away from the optical axis of an objective and focusing the beam onto the specimen.

3.   The method according to claim 2 wherein the deflection of the beam is done before the beam enters the field of the objective.

4.   The method according to claim 2 wherein the deflection of the beam is done inside the field of the objective.

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5. The method according one of claims 2 to 4 wherein the beam is deflected in two steps which are adjusted to each other so that the chromatic aberrations on the surface of the specimen are minimized.

6. The method according to claim 5 wherein the first step is done before the beam enters the field of the objective and the second step is done inside the field of the objective.

7. The method according to one of the preceding claims wherein the two images are used to measure height differences on the specimen.

8. The method according to one of claims 1 to 6 wherein the two images are used to measure the width of a feature recessed in the surface of a specimen, such as a trench or a hole, at the bottom of the feature.

9. The method according to one of claims 1 to 6 wherein the two images are used to measure the width of a feature protruding from the surface of the specimen at the bottom of the feature.

10. The method according to one of claims 1 to 6 wherein the two images are used to compile a stereoscopic image of the surface of the specimen that can be used to produce a 3-dimensional perception.

11. The method according to one of claims 1 to 6 wherein the two images are used to produce a 3-dimensional representation of a feature.

12. The method according to one of claims 1 to 6 wherein the two images are used to measure the width of an edge of a feature.

2o

13.   The method according to one of claims 1 to 6 wherein the two images are used to compile a sidewall profile of a feature.

14.   The method according to one of the preceding claims wherein a reference target is provided in order to determine the precise angle of incidence.

15.   A charged particle apparatus for the examination of specimen comprising:

   a)   a particle source for providing a beam of charged particles;

   b)   an objective for focusing the charged particle beam onto the specimen;

   c)   a detector for measuring at least one secondary product and/or backscattered particles coming from the specimen;

   d)   at least one deflector for deflecting the beam away from the optical axis of the objective so that by the combined action of the deflector and the objective the beam is tilted and hits the specimen with a predetermined angle of incidence;

   e)   a specimen support for bringing the specimen to position corresponding to the tilt of the beam; and

   f)   a scanning unit for scanning the charged particle beam over the specimen, so that an image is generated;

16.   The apparatus according to claim 15 wherein the deflector is located before the objective outside the field of the objective.

17. The apparatus according to claim 15 wherein the deflector is located within the field of the objective.

18. The apparatus according to claim 15 wherein the apparatus comprises two deflectors which are adjusted to each other so that the chromatic aberrations on the surface of the specimen are minimized.

19. The apparatus according to claim 18 wherein the first deflector is located before the objective outside the field of the objective and the second deflector is located within the field of the objective.

20. The apparatus according to one of claims 15 to 19 wherein the objective is a combination of a magnetic lens and an electrostatic lens.

21. The apparatus according to claim 20 wherein an electrostatic retarding field is provided between the electrostatic lens and the specimen.

22. The apparatus according to one of claims 15 to 21 wherein a reference target is provided in order to determine the precise angle of incidence.

23. A method for directing a beam of charged particles onto the surface of a specimen under a predetermined angle of incidence, the method comprising the steps of:

   a)   providing a beam of charged particles;

b)   deflecting the beam away from the optical axis of an objective, said deflection is done in at least two steps which are adjusted to each other so that the chromatic aberrations on the surface of the specimen are minimized; and

c)   focusing the beam onto the surface of the specimen, so that the beam hits the surface of the specimen under the predetermined angle of incidence.

24.   The method according to claim 23 wherein the first step is done before the beam enters the field of the objective and the second step is done inside the field of the objective.

25.   The method according to one of claims 23 or 24 wherein the focusing of the beam is done by a combination of a magnetic lens and an electrostatic lens.

26.   The method according to claim 25 wherein an electrostatic retarding field is provided between the electrostatic lens and the specimen.

27.   A column for directing a beam of charged particles onto the surface of a specimen under a predetermined angle of incidence, the column comprising:

a)   a particle source for providing a beam of charged particles;

b)   an objective for focusing the charged particle beam onto the specimen;

c)   at least two deflectors for deflecting the beam away from the optical axis of the objective so that by the combined action of

the deflectors and the objective the beam is tilted and hits the specimen with a predetermined angle of incidence, said deflectors being adjusted to each other so that the chromatic aberrations on the surface of the specimen are minimized.

28. The column according to claim 27 wherein a first deflector is located before the objective outside the field of the objective and a second deflector is located within the field of the objective.

29. The column according to one of claims 27 or 28 wherein the objective is a combination of a magnetic lens and an electrostatic lens.

30. The column according to claim 29 wherein an electrostatic retarding field is provided between the electrostatic lens and the specimen.

31. A method for the examination of specimen having a trench or a hole on its surface with a beam of charged particles, said method comprising the steps of:

   a)   producing at least two stereo images of the specimen using two different incidence angles; and

   b)   determining the width of the trench or the hole at the bottom of the trench or the hole.

32. The method according to claim 31 wherein from a first image the visible distance between the left top edge and the right bottom edge of the trench or hole and from a second image the visible distance between the right top edge and the left bottom edge of the trench or hole are determined.

33. The method according to one of claims 31 or 32 wherein the width of the trench or the hole at the bottom of the trench or the hole is determined according to the formula:

$$W_b = T_1 B_L / \cos\theta_L + T_2 B_R / \cos\theta_R + h(\tan\theta_L + \tan\theta_R) - W_t$$

where $T_1 B_L$ is the visible distance as measured between the left top edge and the right bottom edge of the trench or hole, $T_2 B_R$ is visible distance as measured between the right top edge and the left bottom edge of the trench or hole, h is the depth of the trench or hole, W_t is the width of the trench or hole at the top of the trench or the hole, and θ_L, θ_R are the viewing angles of the first and the second image respectively.

34. A method for the examination of specimen having a trench or a hole on its surface with a beam of charged particles, said method comprising the steps of:

a) producing at least one images of the specimen using oblique angle of incidence showing a sidewall of the trench or hole; and

b) determining the width of the sidewall of the trench or hole.

35. The method according to claim 34 wherein from the image the visible distance between the bottom edge of the sidewall and the top edge on the opposite side of the trench or hole and the visible distance between the left top edge and the right top edge of the trench or hole are determined.

36. The method according to one of claims 34 or 35 wherein the width of the right and left sidewalls of the trench or hole are determined respectively according to the formulas:

$$W_L = W_t - T_2B_R/\cos\theta_R - h\tan\theta_R$$
$$W_R = W_t - T_1B_L/\cos\theta_L - h\tan\theta_L$$

where T_1B_L is the visible distance as measured between the left top edge and the right bottom edge of the trench or hole, T_2B_R is visible distance as measured between the right top edge and the left bottom edge of the trench or hole, h is the depth of the trench or hole, W_t is the width of the trench or hole at the top of the trench or the hole, and θ_R, θ_L are the right and left viewing angles of the image respectively.

37. A method for the examination of specimen having a feature extending from its surface with a beam of charged particles, said method comprising the steps of:

a)   producing at least two stereo images of the specimen using two different incidence angles; and

b)   determining the width of the feature at the bottom of the feature.

38. The method according to claim 37 wherein from a first image the visible distance between the left bottom edge and the left top edge of the feature and the visible distance between the left top edge and the right top edge of the feature and from a second image the visible distance between the left top edge and the right top edge of the feature and the visible distance between the right top edge and the right bottom edge of the feature are determined.

39. The method according to one of claims 37 or 38 wherein the width of the feature at the bottom of the feature is determined according to the formula:

$$W_b = (X_1X_2 + X_2X_3)/\cos\theta_L + (Y_1Y_2 + Y_2Y_3)/\cos\theta_R - h(\tan\theta_L + \tan\theta_R) - W_t$$

or equivalents thereof, where X_1X_2 is the visible distance as measured between the left bottom edge and the left top edge of the feature, X_2X_3 is the visible distance as measured between the left top edge and the right top edge of the feature, Y_1Y_2 is visible distance as measured between the right bottom edge and the right top edge of the feature, Y_2Y_3 is visible distance as measured between the right top edge and the left top edge of the feature, h is the height of the feature, W_t is the width of the feature at the top of the feature, and θ_L, θ_R are the viewing angles of the first and the second image respectively.

40. A method for the examination of specimen having a feature extending from its surface with a beam of charged particles, said method comprising the steps of:

a)   producing at least one images of the specimen using oblique angle of incidence showing a sidewall of the feature; and

b)   determining the width of the sidewall of the feature.

41. The method according to claim 40 wherein from the image the visible distance between the bottom edge and the top edge of the sidewall of the feature and the visible distance between the left top edge and the right top edge of the feature are determined.

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42. The method according to one of claims 40 or 41 wherein the width of the right and left sidewalls of the feature are determined respectively according to the formulas:

$$W_R = Y_1Y_2/\cos\theta_R - h\tan\theta_R$$
$$W_L = X_1X_2/\cos\theta_L - h\tan\theta_L$$

where X_1X_2 is the visible distance as measured between the left bottom edge and the left top edge of the feature, Y_1Y_2 is visible distance as measured between the right bottom edge and the right top edge of the feature, h is the height of the feature, and θ_R, θ_L are the right and left viewing angles of the image respectively.
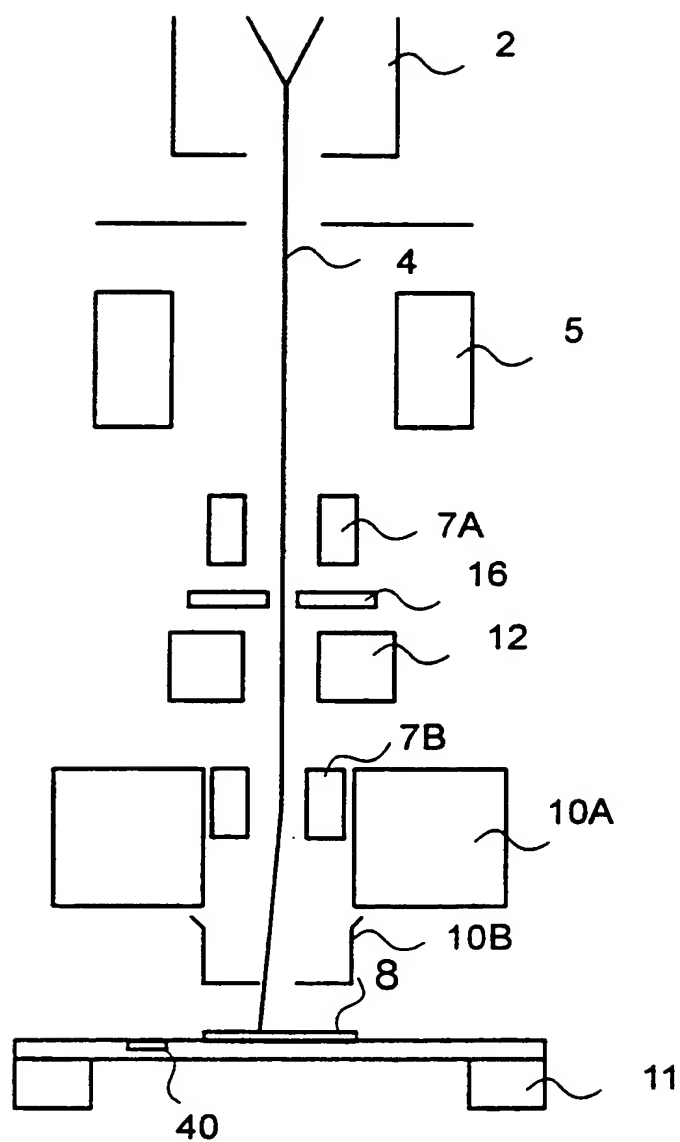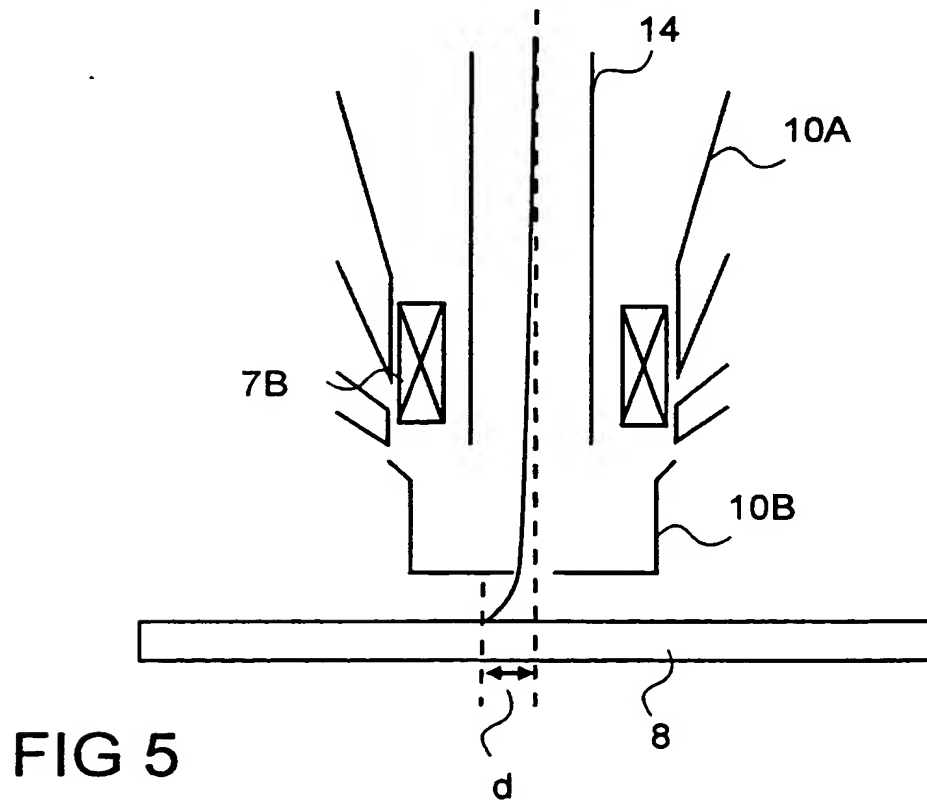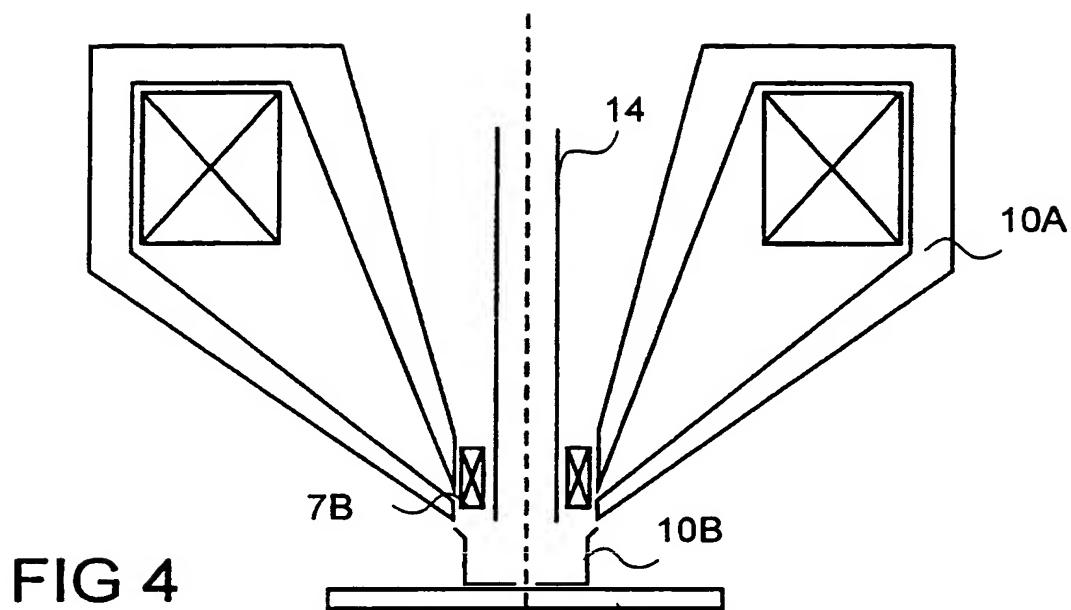
FIG 1

FIG 2

FIG 3

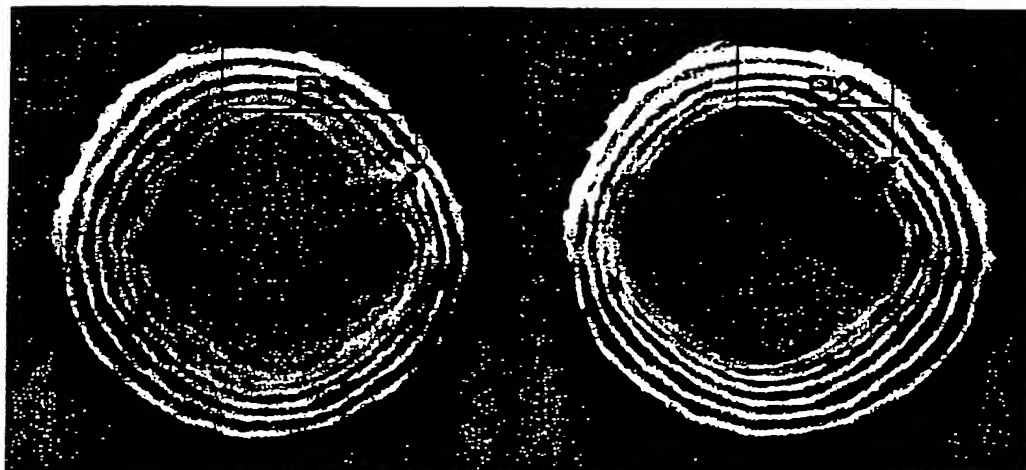FIG 4

FIG 5
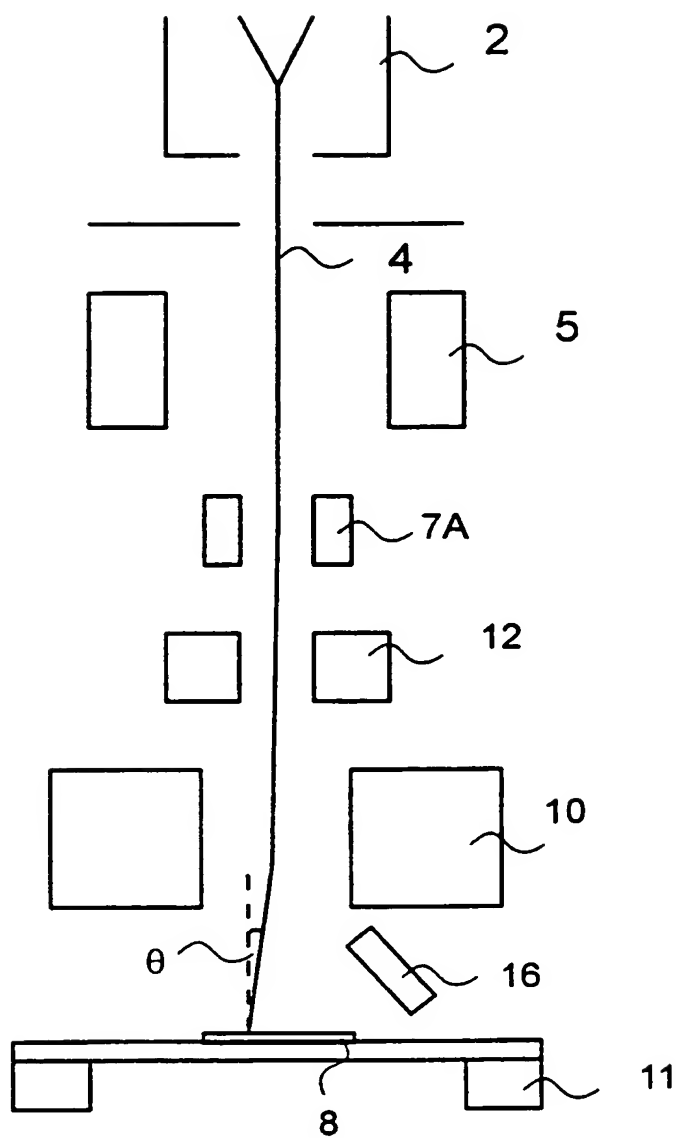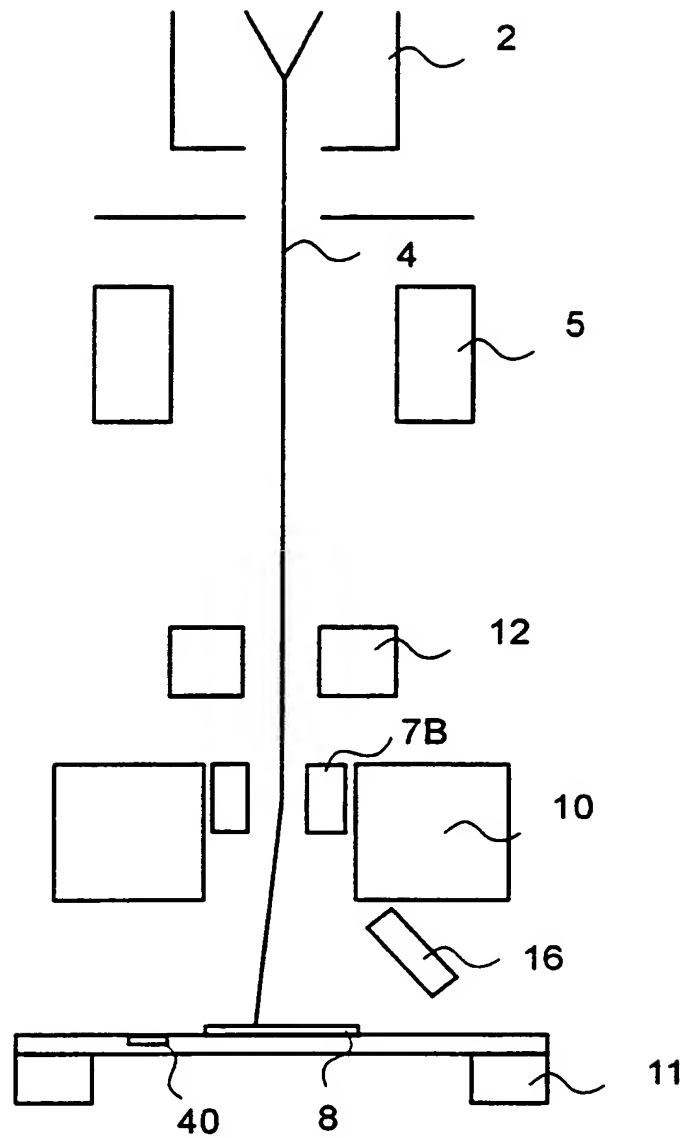
FIG 6A   FIG 6B

FIG 7A   FIG 7B
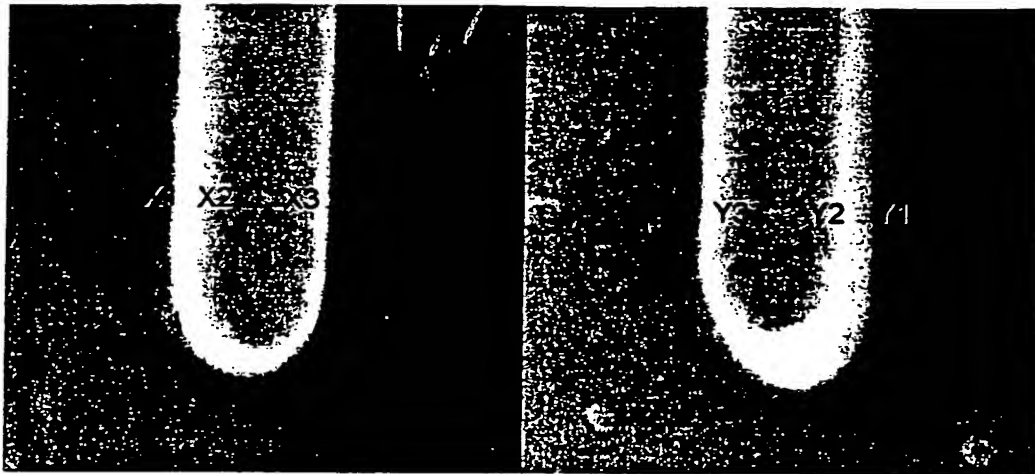
FIG 8A   FIG 8B
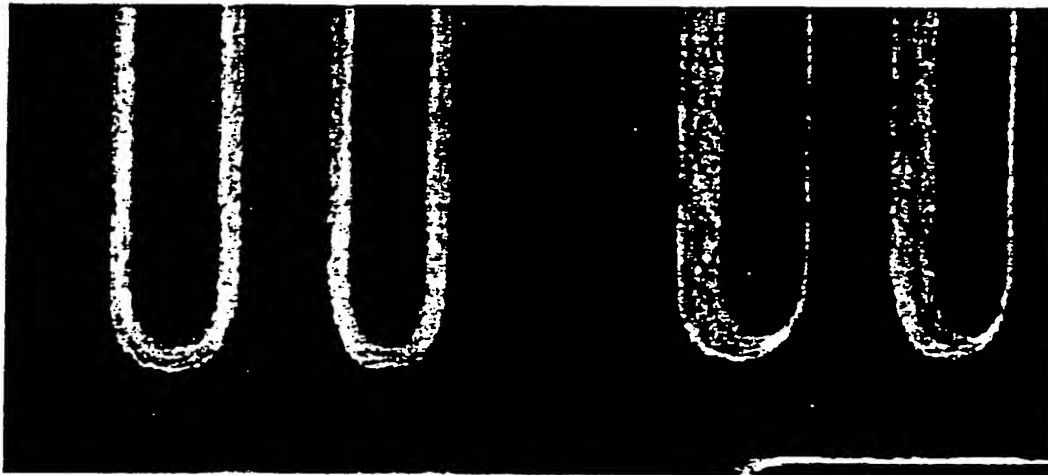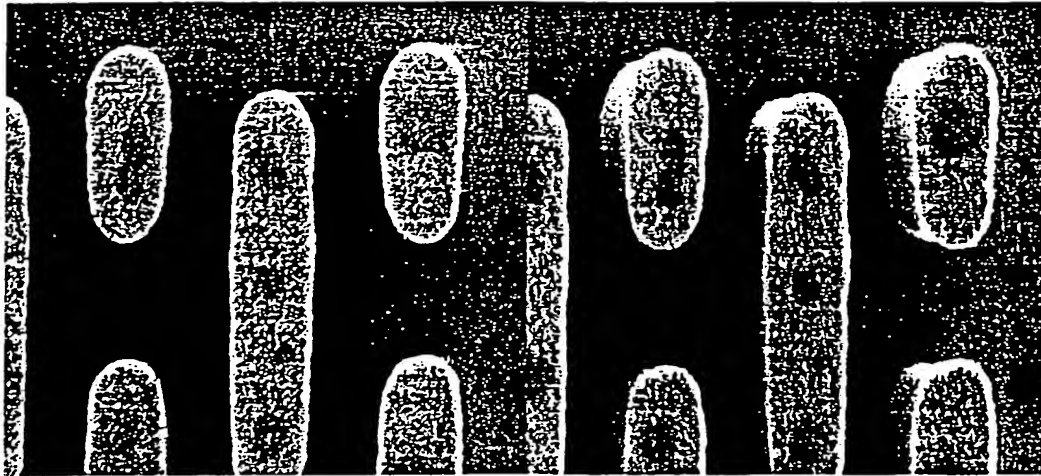

FIG 9A   FIG 9B

FIG 10A　　　　　FIG 10B

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   H01J37/28   H01J37/147   H01J37/153   G01B15/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   H01J   G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	the whole document	4,7-14, 17,18, 20-22

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[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

° Special categories of cited documents :

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search	Date of mailing of the international search report
28 November 2000	0 1. 12. 00

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A		2,3,6, 18,19
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3

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	"SIMULTANEOUS SHIFT AND SCAN IN AN SEM USING SCAN COILS" IBM TECHNICAL DISCLOSURE BULLETIN,US,IBM CORP. NEW YORK, vol. 33, no. 1A, 1 June 1990 (1990-06-01), pages 112-113, XP000120021 ISSN: 0018-8689 the whole document	2-6,19
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3

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FINNES S. J. AND SMITH G. J.: "Nondestructive Slope/Thickness Measurement for Semiconductor Topology" IBM TECHNICAL DISCLOSURE BULLETIN, vol. 26, no. 1, 1 June 1983 (1983-06-01), pages 189-190, XP002153556 New York, US	31,34, 37,40
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3

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-22

    A method and apparatus for stereo-imaging with compensation of the image displacement caused by the tilting of the beam

2. Claims: 23-30, 5, 6, 18-22

    Scanning particle beam apparatus with means for compensating chromatic aberration induced by the deflection means and the objective lens of the apparatus

3. Claims: 31-42, 7-13

    Use of a particle beam microscope for measuring the dimensions of three-dimensional structures on a specimen

INTERNATIONAL SEARCH REPORT

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the International Application that do not comply with the prescribed requirements to such
   an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

   see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this International Search Report covers all
   searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment
   of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report
   covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is
   restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest
☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

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